APPLICATION OF AN ESTUARINE AND COASTAL NOWCAST-FORECAST INFORMATION SYSTEM TO THE TAGUS ESTUARY

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Abstract

Coastal and estuarine nowcast-forecast systems started being developed in the 1990's to provide coastal managers with short-term oceanographic predictions (e.g., waves, tides). Over the years, they evolved in both scope and functionality. Forecasts now simulate more physical processes, and chemical and biological processes are being added. Additionally, better functionalities are being developed to convey data and model results to the user. This paper describes recent advances in the development of a nowcast-forecast system, RDFS-PT, in operation for the Portuguese coast. This system, which provides wave and circulation forecasts, for the Portuguese shelf and two estuaries, and automated data-model comparisons, is now being extended for baroclinic circulation and fecal contamination simulation in the Tagus estuary. Moreover, its interface is being revamped to take advantage of webGIS technologies and to include real-time water quality data from monitoring networks under deployment in the Tagus estuary.

1. Introduction

Coastal and estuarine waters' quality for recreational and bathing uses is a requirement expressed in several national laws and European frameworks (e.g. Bathing Water Framework, BWF). This concern is particularly relevant due to the several uses that occur in these areas, some of which may affect their quality. For instance, domestic effluents or pluvial discharges may lead to fecal contamination events which constitute a potential hazard for public health. Thus, understanding and anticipating these events is essential in the assessment and prevention of social, ecological and economic impacts of both human interventions and climate change in these areas, and, ultimately, to their sustainable management.

Coastal and estuarine nowcast-forecast systems are important tools to support sustainable management, as models predicting capacities allow the anticipation of potential risk situations and the prevention of their consequences. These systems started being developed in the 1990's and have long shifted from research to operational tools, providing coastal managers with short-term oceanographic predictions (e.g., waves, tidal currents), which support emergency operations, harbors and marine resources management, among others. Over the years, they evolved in both scope and functionality. Forecasts now include more physical processes, and are being extended to include chemical and biological processes. Furthermore, better functionalities are being developed to convey data and model results to the user, in order to reach a broad spectrum of users, from coastal managers to the avid recreational person, using desktop and mobile platforms. Regarding water quality, in particular, nowcast-forecast systems are now emerging (e.g. bathingwater.dhigroup.comearlywarningsystem.html, www.waterman.hku.hk/beach/member/Default.aspx), but there are still few nowcast-forecast systems regarding fecal contamination issues, in particular, in Portugal (e.g. Viegas *et al.*, 2009).

This paper describes recent advances in the development of a nowcast-forecast system (Rapid Deployment Forecast System – RDFS-PT, available at http://ariel.lnec.pt) in operation for the Portuguese coast (Jesus *et al.*, 2012). RDFS is a nowcast-forecast information system, based on the deployment of a generic forecasting platform, adaptable to any geographical location, and

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customizable for coastal applications, which was developed by CMOP (Center for Coastal Margin Observation & Prediction, U.S.A.) and adapted and extended by LNEC to the Portuguese coast (RDFS-PT). The system itself integrates a set of numerical models that run in parallel automatically in a high-performance environment. The RDFS-PT platform includes simulations for wave forecast in the North Atlantic and the Portuguese shelf, and for the baroclinic circulation in the Aveiro lagoon and the barotropic circulation in the Tagus estuary. This set of models is capable of coupling waves, tides, storm surges, river fluxes and winds, providing a forecast of sea level variations, currents, temperatures, salinity and waves for a target area.

RDFS-PT is now being extended for water quality (fecal contamination and oil spills), and its interface is being revamped to take advantage of webGIS technologies. The recent advances regarding the RDFS-PT interface and the deployment of baroclinic circulation and fecal contamination of the Tagus estuary are described here.

The paper is organized as follows. Section 2 provides a general overview of the RDFS-PT platform and its recent updates, Section 3 describes the setup and validation of the baroclinic circulation and fecal contamination model of the Tagus estuary, and Section 4 presents the model deployment in nowcast-forecast mode. Final remarks and future developments are presented in Section 5.

2. The RDFS-PT Platform

2.1 Physical Architecture

RDFS's physical architecture comprises several computer servers, clustered around a central file server. This central file server provides archival storage for model outputs, access to model data, and tools for managing the forecasts. Every day each computer server runs one or more forecasts (depending on its capacity). The interaction between physical components and the location of files, web and database servers, as well as how users can connect to RDFS through a web browser are shown in Figure 1a.

The RDFS execution process runs daily, starting forecasts execution scripts and products generation, among others, and interacting with the database in order to get the location of the forecast systems and remotely transferring the products files to the central node.

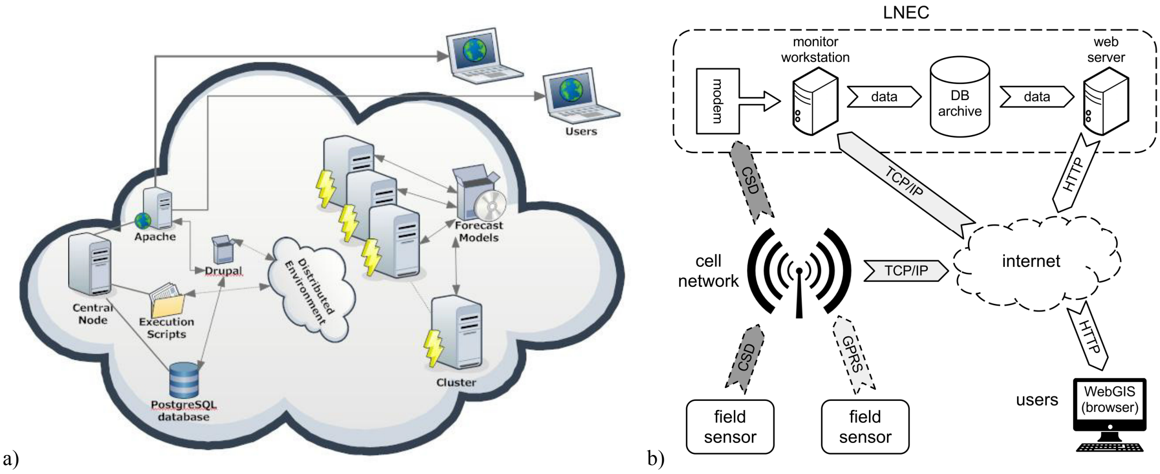


Figure 1. a) RDFS physical architecture and b) general overview of the real-time data collection.

2.2 Technologies and Interface

The RDFS runs on Linux operating system, and its core is composed by a set of Perl scripts, scheduled on crontab, which prepare and launch the simulations for each forecast model. The scripts interact with a PostgreSQL database to retrieve input data to force the models, including river flows, water temperature and atmospheric data.

RDFS main process begins by setting up the environment of the current day, which involves creating the folder structure that will contain all information required to run the simulations, including the preparation scripts. Simulation requirements include the results of the previous run (and/or other forecast models simulation results in the ensemble mode), forecasts from regional circulation models, and atmospheric models and data from field sensors. Most of this information is retrieved from databases and used on-the-fly during the simulations.

After running all simulations the output results are processed, using visualization tools such as VisTrails or the matplotlib library, to generate model forecast products (section 2.4) and data-model comparisons.

The end-user can visualize all the products and interact with the given results, using the RDFS user interface (UI). This UI is basically a customized deploy of Drupal, a PHP-based Content Management System (CMS), that is used to access model metadata, status and products. Recent updates over this interface have been developed and are described below.

2.3 The New RDFS-PT Interactive Interface - WebGIS

Although the existing RDFS-PT UI meets the user requirements, it only provides a static interaction with the model forecast products, lacking the means to localize them geospatially and to display other detailed information besides the products. This shortcoming has created the need to include GIS support for the generated products and to provide a more interactive and intuitive UI for their visualization. In order to overcome those needs, map server support (Geoserver) and Web Map Services (WMS) have been added to the RDFS-PT, allowing geospatial placement of products, as well as model output query capabilities.

With the goal of a more usable UI, a Web Geographic Information System (WebGIS) is being developed in Flex, using the OpenScales library to handle geospatial information. This WebGIS is built in a modular and generic way, allowing not only the visualization of RDFS data, but also spatial data from other sources (Figure 1b).

RDFS-PT products are reused in the WebGIS through georeferencing methods and their deployment in Geoserver is automatic. This deployment is done daily via a set of Perl scripts, which convert TIFF products into GeoTIFF, and a user-agent script that deploys these data into Geoserver. WMS layers are served by Geoserver and displayed in the WebGIS, projected on top of a Bing Map Layer. This new UI allows the user to intuitively manipulate existing products, offering, among others, zooming capabilities and a slider which allows easy navigation through model simulation results in a given interval (Figure 2b). In the future, a capacity to probe on model forecast results and the ability to set simulations on-demand will be added.

2.4 Model Forecast Products

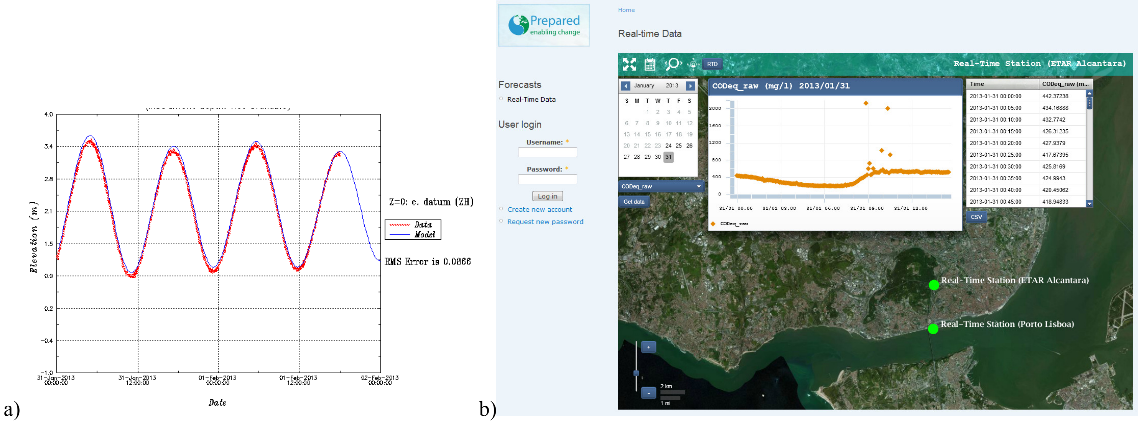
Custom products are automatically produced for each type of forecasting model, depending on the complexity of the simulations and on the variables simulated. Examples of such products are the isolines of water levels, velocities, salinity or water temperature. Images and animations are generated automatically for all products, providing detailed representations of the simulated phenomena. This type of visualization allows the user to iterate over the results from one time step to the next, and also to observe data comparisons between model outputs and field sensor data (Figure 2a).

2.5 Real-time Data Products

Besides embedded forecast products, the new UI also provides the means to access and analyze real-time data (Figure 2b). Field sensors monitoring parameters such as water levels and salinity are installed in the study areas transmitting data to a central server through remote mobile

(Circuit Switched Data - CSD or General Packet Radio Service - GPRS) communication. The transmission occurs at given time intervals, every *n* minutes, and a set of Perl scripts is used to parse and insert these data into a PostgreSQL database. The data are made available to the UI via requests to Java SOAP Webservices which query the database.

In the WebGIS, users are able to choose which sensor data to access, as well as the time interval and parameter monitored. These data are made available to the user in a simple way through line charts, tabular data and CSV files.



a)

b)

Time	CODeq_raw (m...
2013-01-31 00:00:00	442.37238
2013-01-31 00:05:00	434.16888
2013-01-31 00:10:00	432.7742
2013-01-31 00:15:00	426.31235
2013-01-31 00:20:00	427.9379
2013-01-31 00:25:00	417.67395
2013-01-31 00:30:00	425.8169
2013-01-31 00:35:00	424.9943
2013-01-31 00:40:00	420.45062
2013-01-31 00:45:00	418.94833

Figure 2. a) Automatic model validation at the Cascais tide gauge; b) webGIS interface of the RDFS-PT for the Tagus estuary.

3. Barolinic Flow and Fecal Contamination Model of the Tagus Estuary

3.1 Model Description

Hydrodynamics and fecal contamination in the Tagus estuary were simulated using ECO-SELFE. ECO-SELFE is a 3D community model which solves for circulation (SELFE, Zhang and Baptista, 2008) and fecal contamination (Rodrigues *et al.*, 2011), among many other processes (e.g. Rodrigues *et al.*, 2009).

SELFE solves the three-dimensional shallow–water equations and calculates the free-surface elevation, the three-dimensional fields of velocities, salinities and water temperatures. The two models are coupled through the transport equation, taking advantage of the user-defined transport module available within SELFE. The fecal contamination model allows the simulation of the time and space variation of a generic fecal tracer:

$$\frac{\partial C}{\partial t}+u\frac{\partial C}{\partial x}+v\frac{\partial C}{\partial y}+w\frac{\partial C}{\partial z}=\frac{\partial}{\partial z}\left(\kappa\frac{\partial C}{\partial z}\right)+F_c-k_dC-f_sv_s\frac{\partial C}{\partial z} \tag{1}$$

where C is a generic fecal tracer concentration (MPN/m^3), (u,v,w) is the velocity (ms^{-1}), k is the vertical eddy diffusivity (m^{2}s^{-1}), F_c represents the horizontal diffusion term, k_d represents the die-off rate of fecal bacteria (s^{-1}), f_s is the fraction of fecal microorganisms attached to the suspended sediments in the water column (non-dimensional) and v_s is the particle settling velocity (ms^{-1}). Two options are available for the definition of the die-off rate: a user-defined constant coefficient or the formulation proposed by Canteras *et al.* (1995), which presents a direct relation between the die-off rate and the environmental conditions (irradiation, salinity and temperature). The simulation of the settling of the microorganisms follows the approach proposed by Steets and Holden (2003). The fecal tracers considered in the nowcast-forecast information system of the Tagus estuary are the fecal coliforms and *Escherichia coli* (*E. coli*).

Numerically, the coupled model is based on a finite-element/finite-volume numerical method. The domain is discretized horizontally with unstructured triangular grids, and vertically with hybrid coordinates (S-coordinates and Z-coordinates), allowing for high flexibility in both directions.

The parallel version of the coupled model is being used, enabling considerable improvements of computational times. Further description of the model can be found in Zhang and Baptista (2008) and Rodrigues *et al.* (2011).

3.2 Model Setup in the Tagus Estuary

The model setup derived from the application of Costa *et al.* (2012). Simulations aiming the model calibration and validation were performed for the period between July 2011 and September 2011, during which two field surveys (July 15 and September 6) were undertaken in the scope of the project PREPARED (http://www.prepared-fp7.eu/). These surveys covered the area Terreiro do Paço – Alcântara, from the Alcântara wasterwater treatment plant to the estuary. Surveys included measurements of physical, chemical and biological variables and were performed during one tidal cycle. Further description of the field surveys can be found in David *et al.* (2013).

The domain was discretized with a horizontal grid with about 37000 elements and 20000 nodes (Figure 3) and a vertical grid with 20 *SZ* levels (15 *S* levels and 5 *Z* levels). The spatial resolution of the horizontal grid varies from about 1 m in the Alcântara area to 2 km in the oceanic area. The simulation was performed for a period of 92 days with a warm-up period of 2 days, covering the period of the field campaigns, and a time step set to 30 seconds.

Three open boundaries were considered: the Atlantic Ocean, the Tagus River and the Alcântara outfall. The Alcântara outfall aims to represent the discharge to the Tagus estuary of this catchment, which is the largest catchment of Lisbon (with 3200 ha), and has a combined sewer system (which includes the Alcântara wastewater treatment plant) draining to a trunk sewer ("caneiro de Alcântara", 8 m wide and high).

At the oceanic boundary the model was forced by tidal elevations from harmonic analysis of water levels from the Cascais tide gauge. The model included 29 constituents: Z0, SSA, MM, MSF, MF, 2Q1, Q1, RH01, O1, P1, K1, J1, OO1, 2N2, MU2, N2, NU2, M2, L2, S2, K2, M3, MK3, MN4, M4, MS4, S4, M6 and M8. Temperature was forced with time series available from the Cascais gauge database (ftp://www.igeo.pt/Cascais/marégrafo).

At the upstream boundary, the model was forced with the extrapolation of the the Tagus river flow calculated from the water level data available at Sistema Nacional de Informação de Recursos Hídricos (SNIRH, http://snirh.pt) database for the Almourol station. Temperature was forced with time series available from the SIMPATICO (2003) database (http://webserver.mohid.com/simpatico/) at the Salvaterra de Magos buoy and complemented with SNIRH data.

At the Alcântara boundary, the model was forced by a time series of the Alcântara wastewater treatment plant effluent flow (Costa *et al.*, 2012). Temperature and salinity were forced by a constant value, 24 ºC and 2.4 respectively, defined based on the average values of the July field survey. A similar approach was followed to the fecal coliforms and *E. coli* concentrations, which were set equal to 1.2×10^{6} MPN/100 ml and 7.1×10^{5} MPN/100 ml.

Reanalysis data, at a specific point nearest to the Tagus estuary (coordinates 39.047º -9.375º), were obtained from the National Centers for Environmental Prediction (NCEP) from Kalnay *et al.* (1996) and used for the atmospheric forcing.

Initial conditions of temperature were set spatially varying from 15ºC to 24 ºC. For salinity, a spatially varying gradient from 36 in the oceanic boundary to 0 upstream was considered (Costa *et al.* 2012). Similarly, for fecal coliforms and *E. coli* a horizontal gradient was assumed varying from 0 in the oceanic boundary up to 1000 MPN/100 ml, based on the results of Viegas *et al.* (2009) and on the average of the fecal coliforms data available at SNIRH, respectively.

For the definition of the input parameters of the fecal contamination model a preliminary sensitivity analysis was performed and is described next.

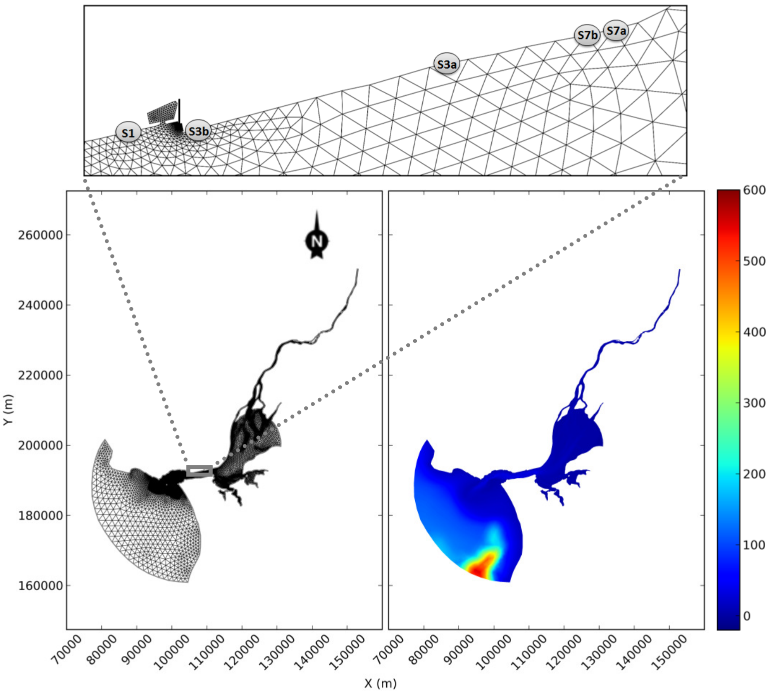


Figure 3. Horizontal grid and bathymetry (in meters relative to Mean Sea Level, MSL), with detailed view of the Alcântara outfall and location of the sampling stations.

3.3 Sensitivity Analysis of the Fecal Contamination Model Input Parameters

The sensitivity analysis consisted in varying one given parameter, assuming a range of values based on the literature available, while the other parameters remained constant. The parameters evaluated were: k_d, f_s and v_s. A reference simulation was set considering: i) the die-off rate based on Canteras et al. (1995); ii) the fraction of microorganisms attached to the sediments equal to 30%, which was determined based on an average concentration of suspended sediments in the Tagus estuary and the formulation of Bai and Lung (2005); and iii) the particle settling velocity equal to 4.17×10^{-6} ms^{-1} (based on Steets and Holden, 2003). Seventeen scenarios (Table 1) were simulated to evaluate the model's sensitivity against the July field surveys' data.

Results (Figure 4) suggest that, in general, the model has a low sensitivity to the fraction of fecal bacteria attached to the suspended sediments and to the particle settling velocity parameters, for the die-off rate evaluated. It should be noted, however, that for lower decay rates (e.g. during winter when solar radiation is lower) the influence of these parameters is more significant (Rodrigues *et al.*, 2009). A significant sensitivity to die-off rate definition is observed. Similar results were obtained for the Canteras *et al.* (1995) and 4 day^{-1} die-off rates, being the ones that lead to the better representation of the data. Thus, based on the results achieved, k_d, f_s and v_s were set equal to: Canteras *et al.* (1995), 30% and 1.6×10^{-5} ms^{-1} (based on Freire, 1993).

Table 1. Summary of the simulations performed for the sensitivity analysis to the die-off rate (k_d), fraction of microorganisms attached to the suspend sediments (f_s) and settling velocity (v_s).

	Simulation																
	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17
k_d (day^{-1})	Canteras et al. (1995)										0.05	1	4	10	37	110	0
f_s (%)	30	10	50	75	100	30											
v_s (m s^{-1})	4.17×10^{-6}					2.66×10^{-6}	2.22×10^{-6}	1.60×10^{-5}	3.01×10^{-5}	7.98×10^{-5}	4.17×10^{-6}						0

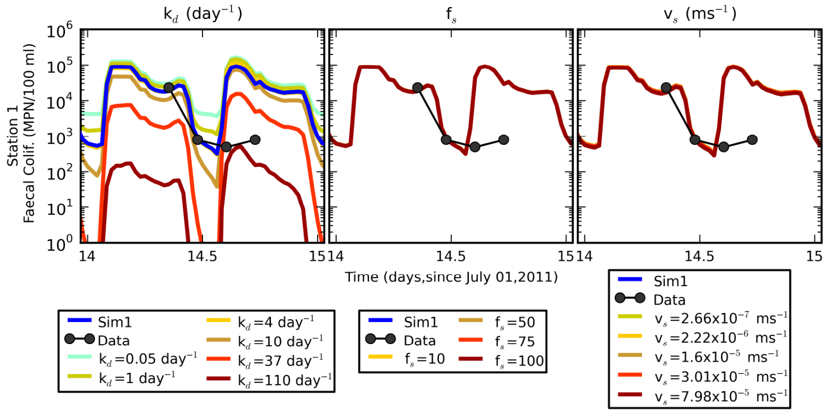


Figure 4. Sensitivity analysis results at station S1. Sim1 refers to simulation 1 where parameters were set as follows: (k_d – Canteras *et al.*, 1995; f_s – 30%; v_s – 4.17x10^{-6} ms^{-1}).

3.4 Model - Data Comparison

Regarding salinity and water temperature, the baroclinic model Tagus estuary had been previously validated with an extensive set of data (Costa *et al.*, 2012). Results achieved here suggest that the model is able to represent the main patterns observed in the field surveys area, with salinity differences generally smaller than 2 and water temperature differences generally smaller than 1ºC (Figure 6). There are, however, some exceptions. At station S1, a salinity increase and a water temperature decrease are observed during the ebb, which may derive from an oceanic water mass that is being trapped near the margin and that the model fails to represent, probably due to a lack of updated bathymetry data in the outflow area. The differences observed in water temperature at station S7a are also explained by bathymetry, since measurements were undertaken over a very shallow location that is not adequately represented in the model.

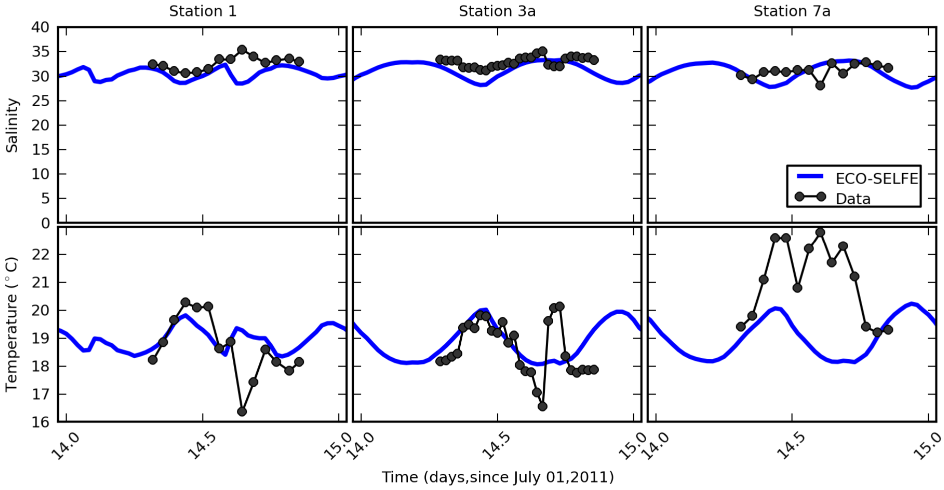


Figure 5. Comparison between data and model results during one tidal cycle at July, 15, 2011: salinity and water temperature.

Fecal contamination tracers' results suggest that the model is able to represent the main patterns observed, both during the tidal cycle at a specific location (Figure 7) and the spatial and temporal variations (Figure 8). The observed differences may derive from the boundary conditions imposed, which were held constant during the simulations and for which data suggest a diurnal variation, namely at the Alcântara outfall (David *et al.*, 2013). Moreover, additional sources that are not being simulated may also contribute to the differences observed. At the Alcântara outfall boundary, the operational model of the Tagus estuary will be forced by forecasts of sewer models (section 4.3) and an extension of the grid to include additional discharges is also under development, both of which may contribute to improve the results. The model will also be continuously validated and improved when deployed in operational mode.

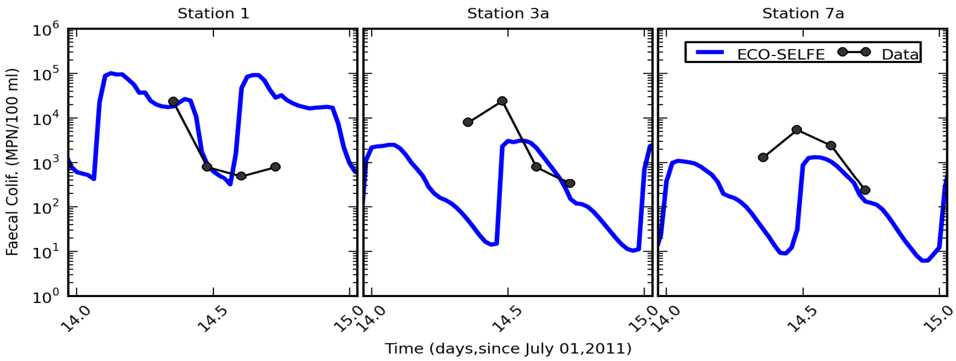


Figure 6. Comparison between data and model results during one tidal cycle at July, 15, 2011: fecal coliforms.

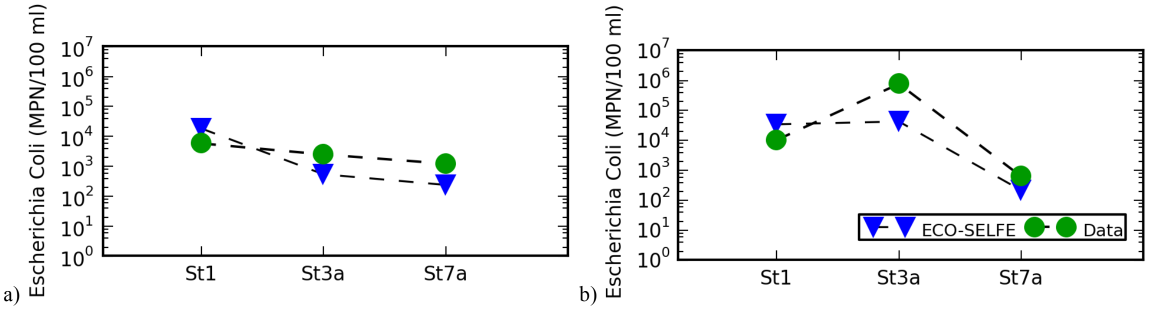


Figure 7. Comparison between data and model spatial variation of average concentrations of *E. coli* on: a) July 15, 2011, and b) September 6, 2011.

4. Deployment of the Operational Forecast Platform RDFS-PT to the Tagus Estuary

The real-time baroclinic and fecal contamination model of the Tagus estuary is deployed using the RDFS-PT platform. Forecasts are run once a day and performed for a 48 hours period. At each simulation automated updates of the oceanic, riverine, Alcântara outfall and atmospheric forcing are done, as described next. Automated data-model comparisons are also available for the circulation parameters and a real-time water quality monitoring system is under deployment (section 4.5).

4.1 Oceanic Forcing

At the oceanic boundary the operational model of the Tagus estuary is now forced with elevations and three-dimensional salinity and water temperature forecasts from the regional ocean model of MyOcean (www.myocean.eu.org/). The downscale of MyOcean to the local model is done by a set of automated scripts that: i) download the forecasts at a user-specified domain, ii) spatially interpolate these results at the boundary points of the user's grid, iii) interpolate the results in time, and iv) build the boundary conditions files for ECO-SELFE.

The fecal contamination tracers' (fecal coliforms and *E. coli*) concentrations are set constant and equal to 0 MNP/100 ml.

4.2 Tagus River Forcing

The river boundary is forced with *near* real-time river flow data from the Almourol station available at SNIRH. A set of scripts allow the download of the current day data, which are then extrapolated for the forecast simulations of ECO-SELFE. A by-pass is used in the operational model running in the RDFS-PT platform when recent data are not available, and climatological river flow, based on monthly means of 1973 (October) to 2013 (April) time series, are used.

Presently, real-time data or model forecasts of water temperature are not available at the riverine boundary. Thus, water temperature climatology, based on monthly average values of water temperature time series available at SNIRH, is used to force the Tagus river boundary. At this boundary, salinity is held constant and equal to 0.

A similar approach to the one used to force water temperature in the operational model was followed to fecal concentrations, since neither real-time data or forecasts are also available at this boundary for these variables.

4.3 Alcântara Outfall Forcing

At the Alcântara outfall, the Tagus estuary model is forced with forecasts from the Alcântara catchment model. The mathematical model of this catchment was built in SWMM and represents sewers larger than or equal to 0.80 m, with a total length of 250 km (David et al., 2013). The model was acceptably calibrated and verified within previous projects and is now being recalibrated for a much larger set of data (Oliveira et al., 2013). Salinity, water temperature and fecal tracers' concentrations at this boundary will be forced based on climatology analysis, derived from historical data of this discharge.

4.4 Atmospheric Forcing

Atmospheric forcing includes forecasts of wind, air temperature, sea level pressure, specific humidity, and shortwave and longwave radiation. For all the variables, with the exception of radiation, forecasts of the WRF 9 km for Europe are used (available at http://www.windguru.cz). Shortwave and longwave radiation forecasts are obtained from the GFS 50 km model, available at http://nomads.ncep.noaa.gov/. A set of scripts were developed to automate: i) download the data and import them to a database; ii) create the netcdf input files for ECO-SELFE.

4.5 Real-time Monitoring and Automated Data Comparison

The circulation model is continuously validated with data from two tide gauges (Cascais and Lisbon, Figure 3a). The coupled circulation-fecal contamination model will be further validated with the data acquired by the on-line monitoring system (located in the Lisbon harbor, Figure 3b), which is being deployed. This real-time monitoring system will include online measurements of chemical oxygen demand (CQO), total suspended solids, pH, nitrates, ammonium, dissolved oxygen, water temperature and salinity, through a set of S::CAN equipment (spectro::lyser, ammo::lyser, condu::lyser, oxy::lyser). A spectrophotometer UV-Vis (spectro::lyser S::CAN) is already operational at the combined sewer overflow structure of Alcântara main trunk (Figure 3b).

5. Final Considerations and Future Developments

This paper presented the recent advances of the RDFS-PT towards the nowcast-forecast information system of the Tagus estuary, which represents an important tool to support the surveillance and monitoring of this estuary, and the management authorities in the decision-making process. The updates of the RDFS-PT platform included the forecast of the baroclinic circulation and fecal contamination forecasts in the Tagus estuary, and also improvements of the visualization tools through a more interactive, user-friendly interface, based on WebGIS.

The nowcast-forecast information system of the Tagus estuary in now under deployment and its operational performance will be further assessed and evaluated.

Future developments are also planned, and will include: additional combined sewer overflow discharges in the pumping sub-systems Terreiro do Paço–Alcântara and Algés–Belém, the deployment of a real-time water quality monitoring system at the estuary, and the development of a Mobile Application capable of providing the same kind of services provided by the WebGIS.

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